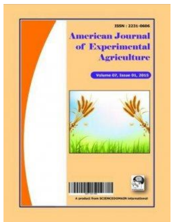

American Journal of Experimental Agriculture
9(4): 1-10, 2015, Article no.AJEA.20220
ISSN: 2231-0606

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Lime-Aluminium- Phosphorus Interactions in Acid Soils of the Kenya Highlands

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Authors' contributions

This work was carried out in collaboration between all authors. Author EMM designed the study, wrote the protocol and wrote the first draft of the manuscript. Authors JPM, ES, PWM and CKG guided on data collection, evaluation and interpretations while author MKN was involved in data collection, data analysis, interpretation and review. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJEA/2015/20220
Editor(s):
(1) Rusu Teodor, Department of Technical and Soil Sciences, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Romania.
Reviewers:
(1) Ade Onanuga, Biology, Dalhousie University, Canada.
(2) Anonymous, Yaradua University, Nigeria.
Complete Peer review History: http://sciencedomain.org/review-history/10546

Original Research Article

Received 17th July 2015
Accepted 30th July 2015
Published 14th August 2015

ABSTRACT

Liming and phosphorus (P) applications are common practices for improving crop production in acid soils of the tropics. Although considerable work has been done to establish liming rates for acid soils in many parts of the world, information on the role of the lime-Al-P interactions on P fertility management is minimal. A green house pot experiment was conducted at Waruhiu Farmers Training Centre, Githunguri to evaluate the lime-Al-P interactions in acid soils of the Kenya highlands. Extremely acidic (pH 4.48) and strongly acidic (pH 4.59) soils were used for the study. Four lime (CaO) rates and phosphorus (Ca $(H_2PO_4)_2$ rates were used. The liming rates were: 0, 2.2, 5.2 and 7.4 tonnes ha^{-1} for extremely acidic soil and 0, 1.4, 3.2, and 4.5 tonnes ha^{-1} for the strongly acidic soil. Phosphorus applications rates were: 0, 0.15, 0.30 and 0.59 g P kg^{-1} soil for the extremely acidic soil and 0, 0.13, 0.26, and 0.51 g P kg^{-1} for the strongly acidic soils. The experiments were a 4^2 factorial laid in a randomized complete block design (RCBD) and replicated

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three times. Data collected included: soil chemical properties and P adsorption. The soils had high exchangeable Al (>2 cmol Al kg^{-1}), Al saturation of (>20% Al) and low P. Lime-Al-P interaction significantly ($P \leq 0.05$) increased soil pH, extractable P, reduced exchangeable Al, Al saturation, P adsorption and standard phosphorus requirements (SPR). Use of 7.4 tonnes ha^{-1} lime in extremely acidic soils and 4.5 tonnes ha^{-1} lime in strongly acidic soils significantly reduced exchangeable Al and SPR by >70%. Lime positively correlated with soil pH, extractable P, and Langmuir maximal adsorption constant and negatively correlated with SPR and exchangeable Al. It was therefore concluded that lime and P positively interact to reduce Al and P adsorption rates in acid soils in the Kenya highlands.

Keywords: Lime; phosphorus; aluminium; standard phosphate requirement; acid soils.

1. INTRODUCTION

Inorganic phosphorus (P) in soil occurs mainly as $H_2PO_4^-$ and HPO_4^{2-} adsorbed onto the surfaces of iron (Fe) and aluminium (Al) oxide, and hydroxides, organic matter layer and amorphous alumino- silicate clay minerals or bound to cations like calcium [1]. Soil acidity is associated with aluminium (Al), hydrogen (H), iron (Fe) and manganese (Mn) on the soil colloids and in the soil solution [2-6] and corresponding deficiencies of the available P, molybdenum (Mo), calcium (Ca), magnesium (Mg) and potassium (K) (3, 4, 5, 6). Although high concentrations of H^+ are toxic to plant roots [7], the main constraint to crop production in acid soils is not high H^+ but increased concentration of Fe^{3+} and Al^{3+} at pH< 5.5 [8]. The occurrence of high levels of Al and Fe in soils gives rise to low pH and low P availability. Thus, wherever Fe and Al are high, a corresponding P stress occurs [9].

Soil acidity and P deficiency are not independent and one of the primary reasons commonly proposed for liming acid soils is to increase the availability of P to plants [10]. The effects of liming on the P supplying power of highly weathered acid soils has, however, been argued differently by different authors. Liming has been reported to increase, decrease, or have no effect on the amounts of soil extractable P [11-15]. Many of these apparent inconsistencies have been attributed to the differences in initial soil pH, nature of soil acidity, soil mineralogy, and the soil P extraction methods used [16].

According to [17], liming can increase P sorption in highly weathered acid soils. The increased P sorption with liming of acid soils was attributed to formation of active x-ray amorphous Al hydroxyl polymers which actively sorb more P than Al^{3+} [18]. The active Al hydroxyl polymers formed can also coat the surface of minerals, thereby modifying their surface charge characteristics [19,20] hence influencing the P- sorption mechanisms by such soils.

Kenyan soils, similar to other agricultural soils of the tropics, are generally low in available P attributable to low soil pH and oxides or/ and hydroxides of Al and / or Fe. Several authors have reported that the available P in the Kenya highland soils is low, ranging from 2 to 5 mg P kg^{-1} soil [21-24]. Various P studies have further indicated that these soils have high P-fixation capacities that transform about 80% of the added inorganic P to forms unavailable for plant uptake [21,25,26]. Several scientists have tested and documented the effect of liming on nutrient availability in acid soils of the western highlands of Kenya [27,28,14]. However, information on the interaction of lime and P on availability of P, as assessed by soil-testing procedures and plant uptake in the Kenya highland, is scanty. The objectives of this study were therefore: (i) to evaluate the lime-P interaction effect on soil acidity and available P, and (ii) To determine the lime-Al-P interaction effect on the P adsorption by two acid soils from Kenya Highlands.

2. MATERIALS AND METHODS

2.1 Experimental Layout and Design

A greenhouse pot experiment was carried out at Waruhiu Farmers' Training Centre, Githunguri, Kiambu County Kenya to determine the lime-Al-P interactions in acid soils. Two composite soil samples representing extremely acid (pH 4.0-4.5) and strongly acidic (pH 5.0-5.5) soils, as described by [29] were used in the study. The experiments were a 4^2 factorial laid down in a Randomized Complete Block Design (RCBD) and replicated three times. Liming rates were chosen to attain 0, 30, 70 or 100% reduction in the amounts of M KCl-extractable Al originally

Table 1. Actual amounts of phosphorus and lime added to the two acid soils

Soil	Lime added (tones ha^{-1})				P added (g P kg^{-1} soil)			
	0%	30%	70%	100%	0 SPR	0.5 SPR	1 SPR	2 SPR
Extremely acidic	0	2.2	5.2	7.4	0	0.15	0.30	0.59
Strongly acidic	0	1.4	3.2	4.5	0	0.13	0.26	0.51

SPR-Standard phosphate requirement

present in the soil while the phosphorus levels added were: 0, 0.5, 1 or 2 times the standard phosphorus requirement (SPR) (Table 1) of the soils used in the study. Burnt lime (CaO) containing about 21% calcium oxide was used in this study while triple superphosphate (TSP) fertilizer (Ca $(H_2PO_4)_2$ was used as P- source. Lime requirement of the soils was calculated using the equation of [30]. The equation aims at reducing the % Al saturation to a level that is commensurate with crop Al tolerance, given as: Lime required $CaCO_3$ equiv. tons/ha = 1.8[Al - RAS (Al + Ca + Mg)/100] where Al = cmol kg^{-1} soil in the original exchange complex, RAS = Required percentage Al saturation, Ca = cmol kg^{-1} soil in the original exchange complex, Mg = cmol kg^{-1} soil in the original exchange complex. A RAS value of 20% was used. Soil characterization data in Table 2 below was used for lime requirement determinations.

Forty eight, 5 kg composite soil sample portions for both extremely and strongly acid soils were weighed and transferred to nine litre plastic pots. The different lime levels were weighed and thoroughly mixed with the soils and incubated at friable state for a period of 21 days. Water was added every 2 days to compensate for evaporative losses and the soils were remixed thoroughly. After incubation, soils from each liming level were air-dried, sieved and returned to the plastic pots. The various P levels were then added and the soils re- incubated at the same conditions for 14 days after which they were air dried. One kilogramme subsamples of the soils were then used for chemical analyses in the laboratory.

2.2 Laboratory Analysis

Soil physiochemical analysis and P adsorption were determined before and after application of treatments. The analysis conducted include: soil pH, exchangeable aluminium, CEC, exchangeable bases and particle size were analyzed as described by [31]. Extractable P was determined Using mehlich double acid method as described by [32] while phosphorus sorption capacities of the soils were evaluated as described by [33] and the P adsorbed data for the two soils fitted into the linearized form of the Langmuir equation.

2.3 Data Analysis

Data collected was subjected to Analysis of Variance (ANOVA) using the Genstat statistical software [34] and means were ranked using Duncan's New Multiple Range Test. Dependency tests and correlations were also conducted to find out if there was a relationship between the various variables.

Table 2. Physiochemical properties of the two acidic soils before the experiment

	Extremely acidic soils	Strongly acidic soils
pH ($CaCl_2$)	4.48	4.95
N (%)	0.19	0.16
OC (%)	1.75	1.83
K (cmol kg^{-1})	0.15	0.20
Na (cmol kg^{-1})	0.58	0.95
Ca (cmol kg^{-1})	1.80	1.23
Mg (cmol kg^{-1})	0.75	3.50
P (mg kg^{-1})	10.50	13.50
CEC	10.82	11.68
Exch. Al (cmol kg^{-1})	3.85	3.90
Exch. Acidity (cmol kg^{-1})	5.79	5.67
AL saturation (%)	55.82	49.66
% Clay	56.32	50.00
% Silt	21.00	17.00
% Sand	22.68	33.00
Textural class	Clay	Clay

3. RESULTS

3.1 The Initial Physical and Chemical Characteristic of the Soils

The tested soils were acidic with pH_{CaCl2} <5.5 (Table 2). Exchangeable Aluminium levels for both soils were > 2 cmol kg^{-1} and % Aluminium saturation > 20%. Both extractable P and Ca were low while CEC was < 15 cmol kg^{-1} soil. The tested soils had clay texture.

3.2 The Effect of Lime - Phosphorus Interaction on Soil Chemical Properties

Lime-Al-P interaction significantly (P<.01) increased soil pH levels (Table 3). Lime rates resulting to 100% reduction in Al^{3+} increased soil pH levels by 2.20 and 2.31 in extremely and strongly acidic soils respectively, compared to the control. Phosphorus did not significantly influence soil pH.

Lime-Al-P interaction significantly (P<.01) increased extractable P in both extremely and strongly acidic soils (Table 4). Lime rates resulting in to 70% reduction in Al^{3+}, promoted the highest amount of extractable P in both soils.

Lime-Al-P interaction significantly (P<.01) reduced exchangeable Al, and % Aluminium saturation in both extremely and strongly acidic soils (Tables 5 & 6). Liming to achieve 100% Al^{3+} reduction, resulted to >50% reduction of the exchangeable Al in both soils compared to the control. Phosphorus use however, did not significantly influence either exchangeable Al or % Aluminium saturation in both soils.

Significant positive relationships were observed between soil pH, lime and extractable P (Table 7). On the contrary, pH, lime and extractable P negatively correlated with exchangeable Al, and aluminium saturation.

Table 3. Soil pH $_{(water)}$ levels determined at the end of the experiment

	Phosphorus levels applied (g P kg^{-1})							
	Extremely acidic soils				**Strongly acidic soils**			
Lime to give	0	0.15	0.30	0.59	0	0.13	0.26	0.51
0% reduction in Al^{3+}	3.96a	4.31a	4.17a	4.19a	3.91a	4.41a	4.07a	3.96a
30% reduction in Al^{3+}	5.30b	5.37b	5.22b	5.15b	5.29b	5.24b	5.29b	5.30b
70% reduction in Al^{3+}	6.24c	6.33c	6.27c	6.37c	5.62c	5.69c	5.53c	5.45b
100% reduction in Al^{3+}	6.63d	6.40c	6.42c	6.39c	6.54c	6.51c	6.38d	6.27c
CV%	0.60	0.60	0.60	0.60	0.90	0.90	0.90	0.90

Values followed by the same letter(s) on the same column are not significantly different at p<0.05

Table 4. Mean extractable phosphorus (mg kg^{-1}) determined from soils at the end of the experiment

	Phosphorus levels applied (g kg^{-1})							
	Extremely acidic soils				**Strongly acidic soils**			
Lime to give	0	0.15	0.30	0.59	0	0.13	0.26	0.51
0% reduction in Al^{3+}	6.80a	12.30a	18.00a	25.00a	6.60a	11.30a	11.30a	11.00a
30% reduction in Al^{3+}	13.00a	16.20a	22.80b	26.50a	12.40b	16.30a	16.80a	23.40b
70% reduction in Al^{3+}	28.20c	32.20c	36.30c	43.20b	41.00c	34.20b	30.60b	35.00c
100% reduction in Al^{3+}	18.40ab	21.20a	35.50c	43.90b	10.90c	30.00b	27.60b	39.70c
CV%	3.10	3.10	3.10	3.10	7.60	7.60	7.60	7.60

Values followed by the same letter(s) on the same column are not significantly different at p<0.05

Table 5. Mean exchangeable Aluminium (cmol kg^{-1}) of the soils at the end of the experiment

	Phosphorus levels applied (g kg^{-1})							
	Extremely acidic soils				**Strongly acidic soils**			
Lime to give	0	0.15	0.30	0.59	0	0.13	0.26	0.51
0% reduction in Al^{3+}	3.75a	3.53a	3.57a	3.48a	3.83a	3.69a	3.76a	3.97a
30% reduction in Al^{3+}	2.91b	2.92b	2.85b	3.03b	2.80b	2.86b	2.74b	2.84b
70% reduction in Al^{3+}	2.41c	2.22c	2.34c	2.29c	2.34c	2.05c	2.22c	2.27c
100% reduction in Al^{3+}	1.82d	1.70d	1.88d	1.62d	1.81d	1.63d	1.72d	1.68d
CV%	1.60	1.60	1.60	1.60	0.80	0.80	0.80	0.80

Values followed by the same letter(s) on the same column are not significantly different at p<0.05

Table 6. Mean Aluminium saturation (%) of the soils determined at the end of the experiment

	Phosphate levels applied (g kg^{-1})							
	Extremely acidic soils				Strongly acidic soils			
Lime to give	0	0.15	0.30	0.59	0	0.13	0.26	0.51
0% reduction in Al^{3+}	69.10a	62.00a	64.90a	60.80a	53.83a	59.35a	51.35a	59.09a
30% reduction in Al^{3+}	45.90b	47.00b	48.30b	55.70a	45.33b	44.70b	46.37b	45.76b
70% reduction in Al^{3+}	45.50b	39.10c	45.20b	44.70c	41.24c	37.45c	35.47c	39.17c
100% reduction in Al^{3+}	31.70c	29.30d	40.50bc	37.80d	28.97d	26.95d	26.66d	26.73d
CV%	7.90	7.90	7.90	7.90	3.20	3.20	3.20	3.20

Values followed by the same letter(s) on the same column are not significantly different at p< 0.05

Table 7. Relationship between soil pH, extractable P, exchangeable Acidity, exchangeable aluminium and liming in acid soils

	pH	Lime	Exch. P	Exch. Al	Al. Sat.
pH	-	0.94	0.38	-0.93	-0.84
Lime	0.94	-	0.29	-0.95	-0.86
P	0.38	-	-	-0.33	-0.28

All correlations had high significant relationship of p<.01

3.3 The Effect of Lime – Al- P Interaction on Phosphorus Adsorption Levels of the Two Soils

The phosphate adsorption isotherms of extremely and the strongly acidic soils were determined by plotting the amounts of phosphate adsorbed (X) against the equilibrium concentrations of phosphate (C). Comparing the highest amount of P adsorbed extremely acidic soils; it is evident that soils treated with different levels of phosphorus had different capacities to adsorb P (Fig. 1). The results of the study showed that maximal P adsorption decreased with increasing fertilizer P application. Soils supplied with 0 mg P kg^{-1} had the highest value of maximum adsorption (1967 mg kg^{-1}) while soils supplied with 3 g P kg^{-1} had the lowest maximal P adsorption (960 mg kg^{-1}).

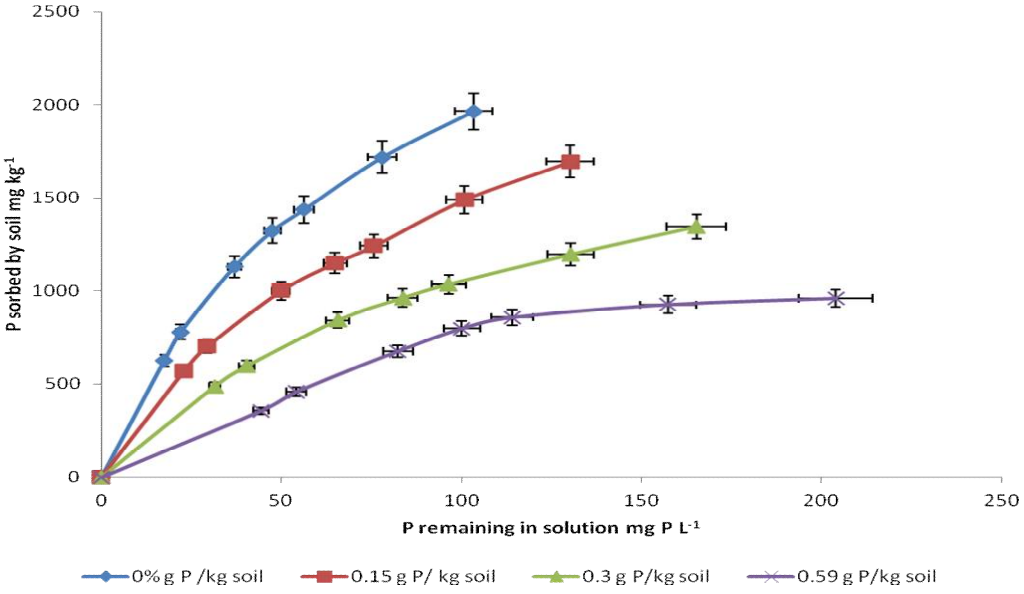

Fig. 1. Phosphate adsorption isotherm of extremely acidic soil treated with different phosphate fertilizer rates (Error bars inserted)

Maximal P adsorption decreased with increasing fertilizer P application in strongly acidic soils (Fig. 2). Soils supplied with 0 mg P kg^{-1} had the highest value of maximum adsorption (1216 mg kg^{-1}) while soils supplied with 2.5 g P kg^{-1} had the lowest maximal P adsorption (889 mg kg^{-1}).

Lime application significantly influenced the capacity of soils to adsorb P (Fig. 3). The results of the study showed that maximal P adsorption decreased with increasing liming rates. Soils supplied with 0 tonnes ha^{-1} lime had the highest value of maximum adsorption (1568 mg kg^{-1}) while soils supplied with 7.4 tonnes ha^{-1} lime had the lowest maximal P adsorption (1242 mg kg^{-1}) in extremely acidic soils. Similarly, soils supplied with 0 tonnes ha^{-1} lime had the highest value of maximum adsorption (1376 mg kg^{-1}) while soils supplied with 7.4 tonnes ha^{-1} lime had the lowest maximal P adsorption (804 mg kg^{-1}) in strongly acidic soils (Fig. 4).

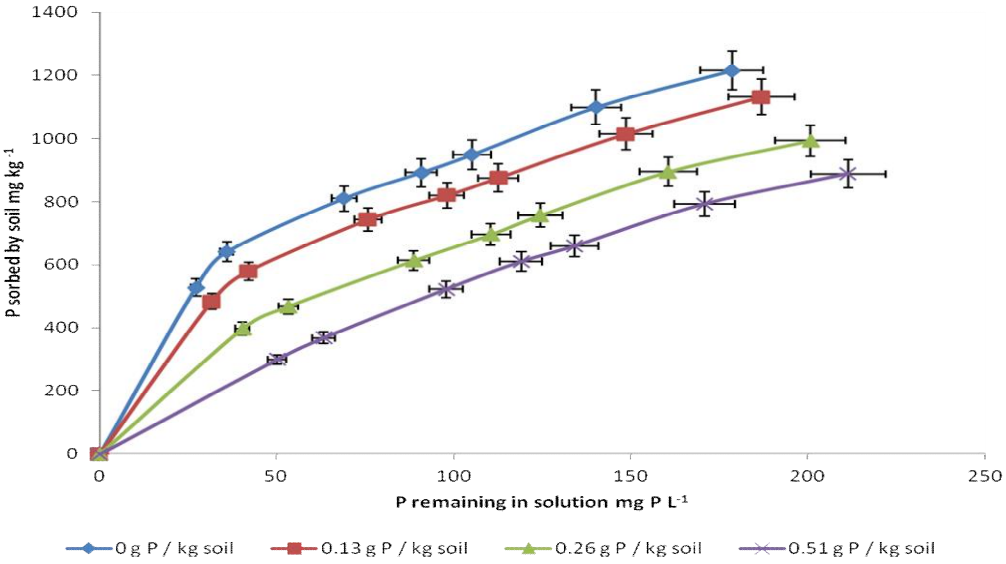

Fig. 2. Phosphate adsorption isotherm of strongly acidic soil treated with different phosphate fertilizer rates (Error bars inserted)

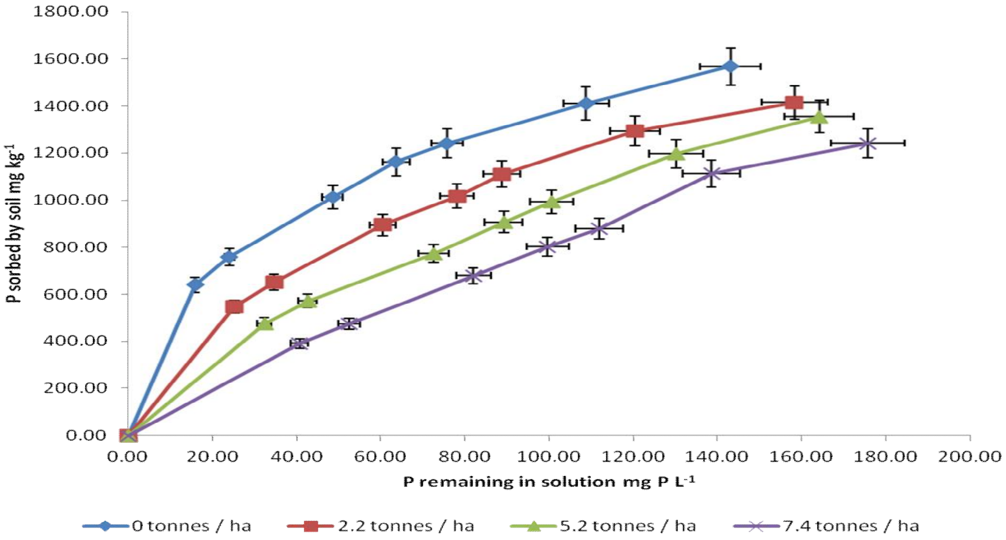

Fig. 3. Phosphate adsorption isotherm of extremely acidic soil treated with different rates of lime (Error bars inserted)

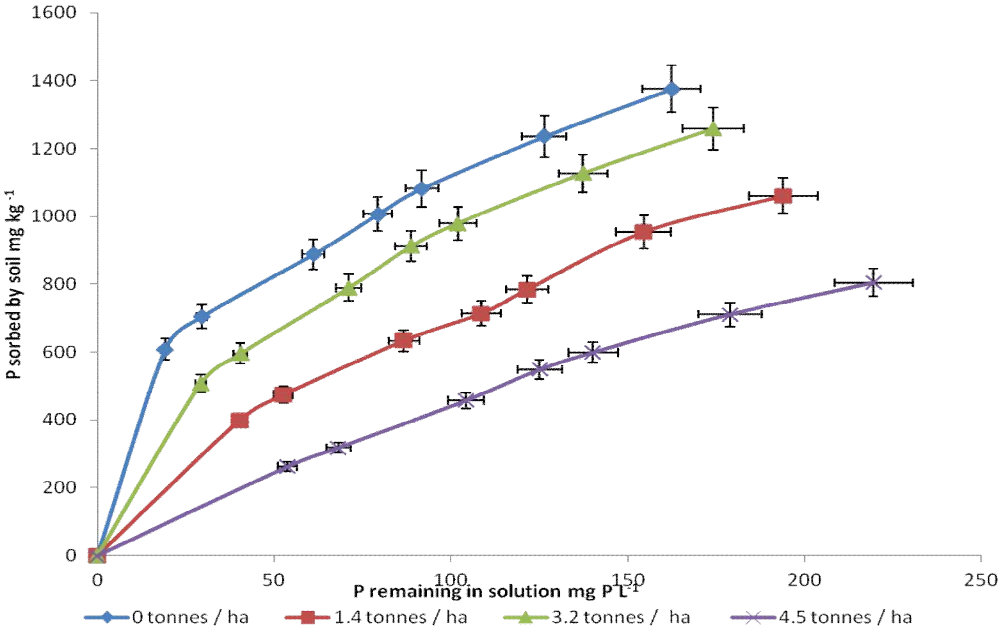

Fig. 4. Phosphate adsorption isotherm of strongly acidic soil treated with different rates of lime (Error bars inserted)

Phosphorus significantly reduced the standard phosphorus requirement (SPR) of the tested acid soils (Table 8). Use of 3.0 g P kg^{-1} reduced SPR by more than 40% compared to 0 g P kg^{-1} in extremely acidic soils. Similarly, 7.4 tonnes ha^{-1} of lime significantly reduced SPR by >81% compared to 0 tons ha^{-1}.

Phosphorus and lime use significantly reduced SPR in strongly acidic soils (Table 9). Use of 2.5g P kg^{-1} significantly reduced SPR by 73% while 4.5 tonnes ha^{-1} reduced SPR by 84% compared to the control.

A significant negative relationship was observed between standard phosphorus requirement of tested acid soils, lime application, langmuir adsorption constants (bL) and langmuir constant related to binding energy (kL) (Table 10). Significant relationships were also observed between lime application, bL and kL.

Table 8. Interactive effect of lime and phosphorus on standard phosphorus requirement (SPR) in extremely acidic soils

Phosphorus (g kg^{-1})	SPR	R^2	Lime (tonnes ha^{-1})	SPR	R^2
0.00	308.71	0.93	0.00	409.63	0.84
0.15	256.41	0.94	2.20	279.25	0.90
0.30	220.87	0.92	5.20	162.13	0.96
0.59	184.08	0.85	7.40	75.34	0.98

Table 9. Interactive effect of lime and phosphorus on standard phosphorus requirement (SPR) in strongly acidic soils

Phosphorus (g kg^{-1})	SPR	R^2	Lime (tonnes ha^{-1})	SPR	R^2
0.00	293.06	0.86	0.00	352.84	0.85
0.13	243.02	0.88	1.40	241.83	0.90
0.26	153.33	0.94	3.20	135.53	0.96
0.51	77.83	0.97	4.50	54.85	0.98

4. DISCUSSION

4.1 Chemical and Physical Properties of the Soils

Levels of exchangeable Ca (Ca<4.0) and CEC< 15 cmolkg^{-1} soil such as identified in this study are low [35]. Soils which are extremely (pH <4.5) to strongly acidic (pH 4.5-4.9) and have aluminium levels (> 2.0 cmolkg^{-1}) have also been reported by [29,36] to be toxic for most plants. Acid soils with such high Al^{3+} ions, low base cations and CEC are characteristics of highly weathered soils, which have lost most of the base cations due to high rainfall and extensive weathering. As a result, the soils have high levels of Fe and Al sesquioxides that may lead to high P fixation resulting to low levels of extractable P [35,37,38]. In addition to leaching of bases, parent material mineralogy also contributes to the soil acidity [38] and P fixation.

Table 10. Relationship between standard phosphate requirement, lime application and Langmuir equation constants of the acid soils

Pair	R	P- value
SPR and lime application	-0.90**	0.00
SPR and Bl	-0.57**	0.00
SPR and Kl	-0.68**	0.00
Lime and Bl	0.54**	0.00
Lime and Kl	0.68**	0.00

*SPR-Standard lime requirement; bL- Langmuir equation adsorption maxima (mg P kg-1); kL- Langmuir equation constant related to binding energy; **Significant at P<.001 level*

4.2 The Effect of Lime - Phosphorus Interaction on Soil Chemical Properties and P-sorption

The increase in soil pH and extractable P and decrease of P adsorption levels and SPR after application of both lime and P could be attributed to increased base saturation leading to replacement of hydrogen ions on the soil surface by bases like Ca^{2+} [4,39]. Neutralization of H^+ results in a pH increase and a shift in the ratio of basic cations adsorbed onto soil particles and in solution [4,10]. Aluminium and iron ions held by negative sites on soil particle surfaces are displaced into soil solution and transformed back into the solid state sesquioxides (e.g Al(OH)3, Fe(OH)3) [4,40]. The Ca^{2+} could either come from lime (CaO) or released upon dissolution of Ca $(H_2PO_4)_2$ [41]. The Ca^{2+} displacement leads to reduced Fe^{3+} and Al^{3+} in solution consequently due to the formation of Al (OH_3) and Fe (OH_3) hence increased P availability in the exchange complex [38-40]. Additionally, pH increase plays a role in stimulating mineralization of P from soil organic phosphorus [16]. Similar findings on reduction of nutrient toxicities and corresponding increase in nutrient availabilities as a result of lime and P have been reported [15,39-42].

5. CONCLUSION

Lime-Al-P interaction significantly increased soil pH levels, extractable P, and reduced exchangeable aluminium, P adsorption and SPR of the acid soils. Combined application of 7.4 tonnes lime ha^{-1} with either 0.30 g P kg^{-1} or 0.59 g P kg^{-1} soil in extremely acidic soils and 4.5 tonnes lime ha^{-1} with either 0.26 g P kg^{-1} or 0.51 g P kg^{-1} in strongly acidic soils significantly reduced SPR and exchangeable Al. It can therefore be concluded that lime-Al - P interactions is important in the management of phosphorus in acid soils of the Kenya Highlands. However, more research is required to ascertain optimal P levels that can be applied to achieve optimal lime-Al- P interactions under field conditions.

ACKNOWLEDGMENTS

The authors express their appreciation to Waruhiu- farmers training centre for provision of research facilities and the Alliance for Green Revolution Africa (AGRA), for funding the research work.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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